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Planning 10 onshore wind farms with corresponding interconnection network and power system analysis for low-carbon-island development on Penghu Island, Taiwan

Yuan-Kang Wu [a,*], Gia-Yo Han [b], Ching-Yin Lee [c]

[a] National Chung-Cheng University, Chiayi 62102, Taiwan
[b] National Taipei University of Technology, Taipei 10608, Taiwan
[c] Tungnan University, Taipei 22202, Taiwan

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ABSTRACT

A five-year, NT$8.09 billion project to turn Penghu, Taiwan, into a world-class low-carbon island was formally launched in 2011. The project is a major milestone in Taiwan's development of renewable energy. The initiative, which will install large onshore wind power generators, is predicted to reduce carbon dioxide emissions by more than 50% in 2015 from 2005 levels. The study examines the plan for large onshore wind farms and the corresponding connected network, and performs simulation analysis for the integrated wind power system. Simulation results of the system impact analysis will be a valuable reference for the government and power utility. Additionally, this study examines several successful renewable development projects on other islands worldwide, the environmental conditions for the Penghu wind energy project, and the preplanning process for the Houliao Energy Park on Penghu.

Contents

1. Introduction

In response to need to reduce carbon emissions and consensus at the National Energy Meeting to build low-carbon homes, Taiwan's central government is actively promoting Penghu Island as Taiwan's first demonstration area for low-carbon cities. The initial reduction target for carbon emissions is 50% by 2015. The low-carbon island program will benefit Penghu in terms of its image, energy usage, available resources, industry, and livelihood. Penghu will become a demonstration model for carbon reduction technology, and renewable R&D achievement [1]. The low-carbon island plan covers renewable energy, energy conservation, green transportation, low-carbon buildings, and resource recycling. Each area has its own implementation guidelines and quantitative targets. For renewable energy, several onshore wind farms with a total capacity exceeding 100 MW will be constructed. According to the Bureau of Energy, advantages of the low-carbon island project in Penghu are power generation, energy savings, fuel

* Corresponding aouthor. Tel.: +886 5 272 0411x33232; fax+886 5 2720 862.
E-mail addresses: allenwu@ccu.edu.tw (Y.-K. Wu).
t6319017@ntut.edu.tw (G.-Y. Han), cylee@mail.tnu.edu.tw (C.-Y. Lee).

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savings, water savings, and waste and transportation benefits. Power generation from renewable energy, especially large onshore wind farms, is key to the low-carbon island project.

To promote Penghu as a low-carbon island, the Penghu County Government has established a local energy company, and the Houliao region will be home to the first energy demonstration park in Penghu. The Houliao Energy Park will have a groundwater reservoir, seawater desalination area, wind power area, Photo Voltaic (PV) power area, green woodland area, energy demonstration area, and administrative and management areas. The park will cover 591 ha, and wind power will be the main renewable energy.

Based on historical statistics, wind energy on Penghu is the highest in Taiwan [2]. The capacity factor of wind power generation by the Jhongtun Wind Farm in Penghu can attain an annual average exceeding 40% [3]. The Penghu County Government has identified suitable wind farm sites by assessing wind conditions, geological conditions, topography, landscape, bird populations, ecology, the human population distribution, construction conditions and their impacts, land acquisition, transportation, and power grid in the Penghu area. Planning the power grid connection is very important to the development of wind power. The existing power system in Penghu is an independent island system which encompasses the Jianshan Thermal Plant, Husi and Magong substations, and Jhongtun and Husi wind farms. In the future, after the Taiwan–Penghu submarine cable is complete, the Jianshan plant will function as a backup power plant and a primary substation will be constructed to reduce the 161 kV submarine cable voltage to 69 kV to supply the electricity required by Penghu Island. However, current power system planning for Penghu has not considered possible development of wind farms around the island and the future power grid connection. Therefore, system simulations and analyses of possible plans are needed to identify the possible impacts of system disturbances on the system and provide responsive countermeasures.

The study explores key issues related to large onshore wind farms and their corresponding power grid connection plans for Penghu as a low-carbon island. Additionally, in-depth system simulation and analysis are conducted, and simulation results are used to assess the feasibility of constructing large wind power projects. Successful experiences of with renewable energy on islands worldwide and the necessary environmental conditions for developing wind power on Penghu Island are described.

2. Successful experiences in the development of renewable energy on islands

The Danish government chose Samso Island in 1998 as its demonstration island to generate 100% renewable energy. The island, which has a total area of 114 km^2, is home to roughly 4400 residents. To gain the support of residents, the Danish government invested in local wind power projects. The development strategies for Samso Island were as follows:

(1) Used renewable energy to improve energy utilization efficiency for heating, electricity, and transportation.
(2) Use local biomass energy as fuel to supply the heat to island homes.
(3) Construction onshore and offshore wind turbines.
(4) Gradually replace gasoline for transportation vehicles with electricity and hydrogen.

Samso Island currently has an offshore wind farm with ten wind turbines (each has an installed capacity of 2.3 MW) and three onshore wind farms with a total of eleven wind turbines and an installed capacity of 11 MW. The island's electricity transmission system, which is rated at 15 kV, has diesel backup generators and supplementary submarine cable connections to other power systems. Additionally, three biofuel-based heating systems with supplementary solar energy are used. All electricity is generated by wind power, and 75% of the heat is from solar and biomass energy. By the early part of the last decade, the load demand in Samso Island was completely provided with renewable energy, and by 2007, the emission of carbon dioxide in the island decreased by 100% [4].

Utsira Island [5,6], Norway, has a population of about 250 people. It was dependent on electricity provided through an 18-km-long undersea cable from the mainland. Utsira Island opened the world's first autonomous integrated energy storage system that stores wind power. Utsira Island has an average wind speed of at least 10 m/s. Two 600 kW wind turbines supply electricity; excessive electricity is used to electrolyze water into hydrogen and this energy is stored in hydrogen storage devices to prepare for demand on windless days. When a wind turbine stops generating power on weak-wind or windless days, fuel cells and hydrogen fuel generators convert stored hydrogen into electricity. This system is subject to assessments of operational benefits and is used for planning improvements, such as increasing the capacity of the hydrogen storage tank and electrolyzer, replacing the hydrogen engine with fuel cells, and using other renewable energy sources such as solar and biomass power in addition to wind power.

Australia's King Island is another successful case in the development of renewable energy. King Island's power generation and storage facilities have three 1.6 MW and one 1.2 MW diesel generator units, three 250 kW wind turbines and two 850 kW wind turbines, Vanadium Redox rechargeable flow batteries, frequency control resistors, and a 100 kW solar power system. Energy stored by the system is primarily used to support wind power by providing a flexible power generation schedule; frequency control resistors are mainly used to absorb excessive wind power to prevent wind turbine shutdown when wind speeds are excessive. In order to reduce the diesel consumption on the island, a stand-alone wind–hydrogen system in King Island was proposed in [7], in which an existing wind–diesel power system was analyzed, and different configurations of additional hydrogen energy system was simulated to determine a suitable hydrogen integrated configuration and set up the prototype system for the island. Also, after approval by the King Island Council, another wind turbine group with a capacity of 4 MW will be built in near future. With these new wind turbines and frequency control resistors, power generation capacity will be increased. In addition to wind and solar energy, King Island also seeks alternative energy sources, including biodiesel to replace petroleum, and invests in research and development of ocean energy, including tidal power and wave power technologies.

The Spanish government intends to transform El Hierro Island [8,9] into a 100% renewable energy island. El Hierro Island is the world's first demonstration island combining wind and hydropower. Hydroelectric power can overcome the unpredictability of wind. On normal days, wind power supplies the island's electricity and excessive power is used to pump water from a lower reservoir to an upper reservoir. When wind power is insufficient, water in the upper reservoir is drained into the lower reservoir to generate electricity. If both wind power and the water level in the upper reservoir are insufficient, diesel generators are used to generate power. The total capacity of the island's diesel generators is currently 8.3 MW, wind farm capacity is 9.35 MW, and hydropower capacity is 9.9 MW. As the wind power on El Hierro Island has reached 30% penetration, it serves as a good demonstration system for research on the transient impact of the system

on stability. In addition to wind, solar radiation resources on El Hierro Island are abundant, and a solar thermal energy project is now underway. El Hierro Island is also assessing the feasibility of using garbage, animal waste, and other wastes as biomass fuels. The associated studies of hybrid renewable energy system in El Hierro Island were shown in [10] and [11]. In [10], the authors investigated the application of hybrid closed-loop energy system from technical, regulatory and political perspectives. The hybrid energy system combines multiple renewable energy and storage technologies, and can be seen as an alternative to diesel fuel fired electrical generators. About the technological, economic and socio-political conditions surrounding the hybrid electrical generating system on El Hierro Island were explored in [11], in which a modified level cost of energy (LCOE) model was presented for both existing diesel energy system and the renewable energy hybrid closed-loop system to determine the economic crossover point of project selection. The authors also demonstrated that the model also functions as a policy that makes tool for determining the effects of emissions pricing, political project value, and net present value analysis on comparing the two types of systems.

Greece has many large and small islands. Most power on western islands is from the mainland Greece; however, most islands in the Aegean Sea have their own power systems. The Greek islands are ideal for wind and solar energy generation. Furthermore, the potential for developing geothermal and biomass energy resources is good. Crete, Greece's largest island [12,13], has the largest power system. The highest voltage for power transmission on the island is 150 kV. The power system has three traditional fuel power plants (22 units with an installed capacity of 725 MW), and 12 wind farms (an installed capacity of 105 MW, accounting for 12.5% of total installed capacity). Since 2000, wind power has accounted for about 10% of total generated power, and maximum instantaneous wind power accounts for 39%. Due to the occasional high instantaneous wind power penetration, electricity frequency sometimes oscillates, such that low-frequency protection relays for wind power generators engage. Kythnos Island [14–17], another Greek island, has high wind power penetration. Roughly 10.2% of the island's electricity is from wind power, and 1% is from solar power. Due to the high penetration of renewable energy, the island's energy storage system was analyzed for system improvement and to reduce the system's impact on stability. According to analytical results, construction of an appropriate storage system will reduce operating costs by 2.16%.

Jeju Island in South Korea has developed wind power generation actively in recent years. The demonstration project of Jeju Island for wind power generation is planned by the Korean Government's Ministry of Trade, Industry and Energy (MOTIE) and the Korea Institute of Energy Research (KIER), and started operating in February 1995 [18]. Jeju Island has a total area of about 1800 km^2 and a population of nearly 540,000. The annual mean wind speed was estimated to be 5.3 m/s at a height of 25 m above ground level; the mean annual wind energy density was calculated to be 200 W/m^2 at the same height by assuming a Weibull wind speed distribution. The capacity of wind power planned to be installed in Jeju system reaches 250 MW [19] and until 2010, a total capacity of 88 MW wind power generation systems was in operation [20]. Because the total wind power capacity in Jeju Island is considerable compared to the minimum load of 300 MW, the necessity to limit the wind power installation in Jeju Island has become an important issue. In additional to wind power, the government of South Korea also has outlined basic goals in 2050 to foster the other types of renewable energy in Jeju Island: 130.1 MW of geothermal energy accounting for 15% of total renewable supply, 449.7 MW of solar PV power accounting for 7.5% of total energy supply, 161 kl of energy by biogas, 455 MW of energy by fuel cells accounting for 35% of renewable energy supply [21].

Many other countries are developing renewable energy islands. For instance, the US Hawaiian Islands [22–24] are rich in renewable energy resources, including wind, solar, geothermal, biomass, small hydro, pumped energy storage, and ocean energy. Therefore, the state government and the Hawaiian Electric Company (HECO) in 2008 signed the Energy Agreement to reduce Hawaii's dependence on imported fossil fuels and develop local renewable energy sources [25]. In this agreement, the goal is to obtain 40% of the islands electricity generated from renewable energies by 2030 (10% by 2010, 15% by 2015, and 25% by 2020). Germany's Pellworm Island [26,27] has been developing renewable energy technologies since 1997, focusing on wind power, biomass energy, and related energy storage technologies. The island currently has 16 wind turbines with a total installed capacity of 5.9 MW. To reduce risk from variations in wind energy, biomass energy from burning straw and animal waste has been used on the island to compensate for wind power variation. Pellworm Island built its first solar power generation facility in 1983; its installed capacity is 300 kW. Currently, the total area of installed solar panels on Pellworm Island is 8000 m^2. Spain's Canary Islands are also developing renewable energies based on wind and solar power. The island's water supply is mainly generated by reverse osmosis desalination. In terms of energy consumption by seawater desalination, renewable energy and the desalination plant were recently integrated; thus, a pumped hydro storage power plant integrated with renewable energy was an another valuable study issue [28,29].

3. Environmental conditions for developing wind energy on Penghu

Several factors, including meteorology, geology, natural disasters (e.g., earthquakes, lightning, and typhoons), resident acceptance, environmental impact [30], and conditions for power grid connection, will determine whether the Penghu Island can develop wind power. Penghu has a meteorological environment characterized by a subtropical marine monsoon climate with hot summers and dry winters with an annual average atmospheric pressure of 1013.1 hPa at sea level; average annual temperature of 23.2 °C; annual average rainfall of 954.5 mm; 2097.4 annual average sunshine hours, and annual average relative humidity of 81.2%. The prevailing wind direction is north by northeast and is strongest from October to February. Fig. 1(a) and (b) show statistical wind maps for Penghu Island in 2010 and 2011, respectively. The annual northeast monsoon winds in Penghu are generally stable and in the northern and north-by-northeast directions.

The main outcrop rock on the Penghu islands is basalt, sedimentary rocks, volcanic tuffs, or tuffaceous sandstone breccias occur in certain areas; these rocks are beneficial for constructing the foundations of wind turbines.

Potential natural disasters in Penghu can be categorized as earthquakes, lightning, and typhoons. According to statistics from the Earthquake Forecast Center, Central Weather Bureau, only 18 earthquakes with a seismic intensity of 3, and 11 earthquakes with seismic intensity of 4 hit Penghu between December 1993 and May 2011. During the last 18 years, the largest earthquake had a seismic intensity of 4. To date, earthquakes have had little effect on wind turbines on Penghu. Additionally, according to statistics from the Taiwan Power Research Institute, 546 lightning strikes hit within a 10 km radius from the Penghu weather station during the last five years (2006–2010), which is equivalent to a

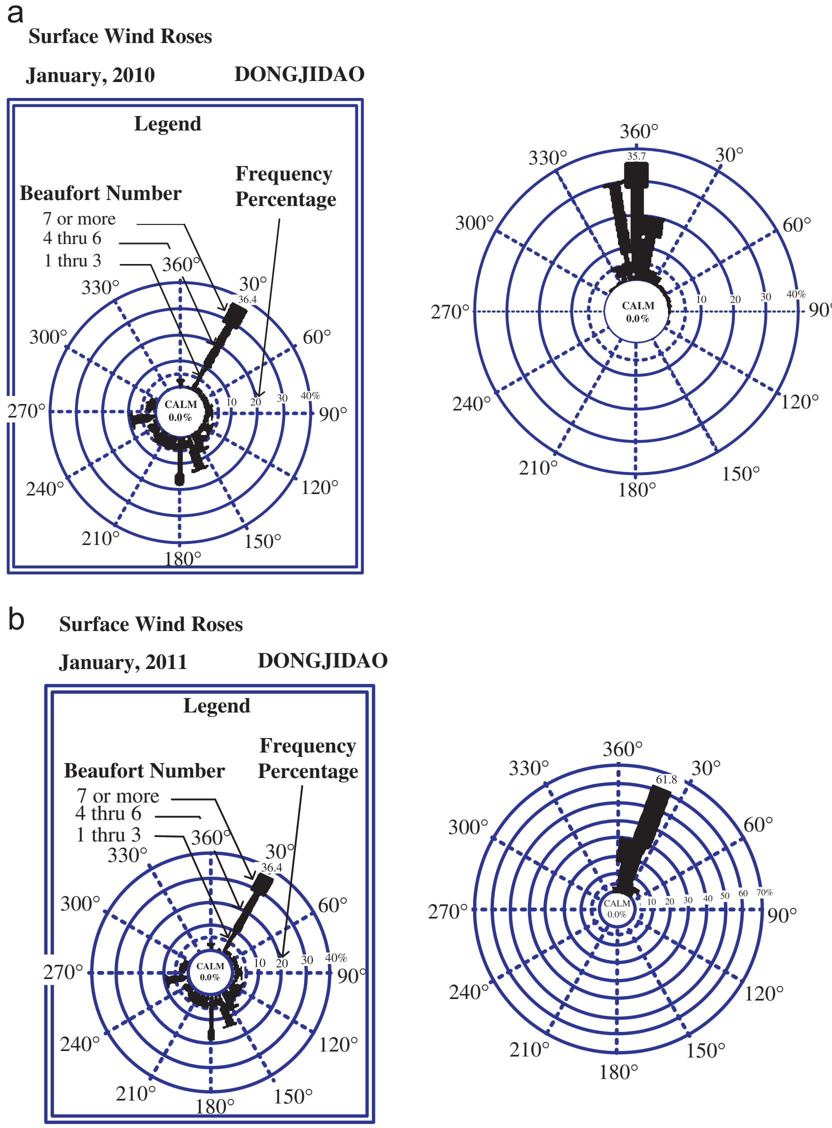

Fig. 1. Wind statistical maps for Penghu Island.

lightning density of 0.3476 strikes/km^2/year and is lower than the average lighting density on mainland Taiwan.

Taiwan is located in the path of Northwest Pacific typhoons. The typhoon season is from June to September. Many buildings can be damaged by high wind [31]. According to typhoon statistics, Penghu Island will be hit by a destructive typhoon every 15–20 years. For example, Typhoon Wayne, which hit Penghu in 1986, had instantaneous wind speeds of up to 68 m/s and Typhoon Chebi had instantaneous wind speeds exceeding 54.8 m/s. Notably, these wind data were measured by a weather station 10 m above sea level, not at the height of a typical wind turbine, which is about 40–60 m high; thus, wind speed at the height of wind turbine towers will be higher. To install wind turbines in the Penghu area, one must consider the wind resistance of wind turbines. Further, corrosion, a very serious problem on Penghu, often damages the insulation of stator coils of wind turbines in the Jhongtun Wind Farm and causes short circuits; thus installations of wind turbines must prevent corrosion.

The power system in the Penghu area is a typical isolated island system with a maximum voltage of 69 kV. The major power generation sources are 12 thermal power units in the Jianshan Power Plant and 14 wind turbines on the Jhongtun and Husi wind farms. Total installed capacity for power generation, including traditional thermal power plants and wind power, is 130.2 MW. For the resident load on Penghu Island, the seven 69 kV/11.4 kV primary transformers in the Magong and Husi substations meet the demand of 32 major feeders for an off-peak load of approximately 28 MW in winter and peak load ≥ 70 MW in summer. To avoid salt corrosion, most power transmission systems on Penghu Island are placed underground. However, due to the high charging capacity of feeders, system voltage is often too high in winter. Two 3 MVAr reactors have been installed in the Husi substation and two 5 MVAr reactors have been installed in the Magong substation to solve overvoltage problems by connecting reactors to the system in winter. In the future, in conjunction with the construction of the Taiwan–Penghu submarine cable [32], one primary substation and the Jiangmei secondary substation will be constructed on Penghu Island, and the Jianshan Power Plant will be the backup power plant. In other words, Penghu Island will have one primary substation and three secondary substations (i.e., the Jiangmei, Husi, and Magong).

Phase 1 and Phase 2 of the Jhongtun Wind Farm are connected to the secondary side of the Husi substation through separate 11.4 kV feeders. Although this connection configuration meets the requirements of Taipower, Taiwan's unique power company,

and its technical guidelines for connecting renewable energy power generation systems, construction cost for these two 13-km-long transmission lines is high. For wind farms established on the island in the future, installing dedicated lines for wind turbines in each region to connect to the substation is impossible. Rather, a wind power transmission line that goes around the island can collect wind power from each region and then a dedicated line can be connected to the substation; however, this wind power transmission line may exceed 30 km in length. To avoid high transmission loss and to meet requirements stipulated in Taipower's technical guidelines for connecting renewable energy power generation systems, the dedicated line for power transmission around the island for wind power has a voltage rating of 69 kV in this study. The wind farm in each region is connected through 11.4 kV/69 kV step-up transformers with a capacity of 25 MV A into the 69 kV transmission system. If total installed capacity of a wind farm in one region exceeds 20 MW, the number of step-up transformers will be increased to prevent transformer overloading. Table 1 shows possible planned installed capacity of wind farms in each Penghu region.

Table 1
Installed capacity of each planning wind farm in Penghu Island.

Wind farm	Capacity (MW)
Longmen	25.2
Jiangmei	7.2
Citou	7.2
Jibei	18
Chihkan	18
Tongliang	10.8
Siyu	32.4
Siao Chih Jiao	14.4
Husi	5.4
Jhongtun	4.8
Sum	143.4

Fig. 2 shows the configuration of wind farms islandwide and the single-line schematic diagram. Planned wind farms around Penghu Island are concentrated mainly on the northern windward side to maximize wind energy resources. Fig. 2 shows the 69 kV single-line schematic diagram of the system and the connection point for wind farms in each region. The planned wind power transmission system around the island sequentially incorporates the Siao Chih Jiao Wind Farm, Siyu Wind Farm, Tongliang Wind Farm, Chihkan Wind Farm, Jibei Wind Farm, Citou Wind Farm, and Jiangmei Wind Farm and is then connected to the 69 kV primary side of the Jiangmei substation. The plan for connecting the Jiangmei substation to the Husi substation in the Jianshan Power Station was developed by Taipower.

Fig. 2 shows the single-line schematic diagram of the entire Penghu system for simulations. Parameters for the dedicated line around the island were generated by considering unit length specifications for a typical 69 kV cable, such that the simulation will resemble an actual case. This system contains planned wind farms around the island, the dedicated transmission line, and existing feeder system, which includes twenty 11.4 kV buses, sixteen 69 kV buses, eighteen 11.4 kV/69 kV 25 MV A transformer, and two 69 kV/161 kV 200 MVA transformers.

4. System simulation

Based on circuit design and planned system parameters discussed in the previous section, simulations of the Penghu system

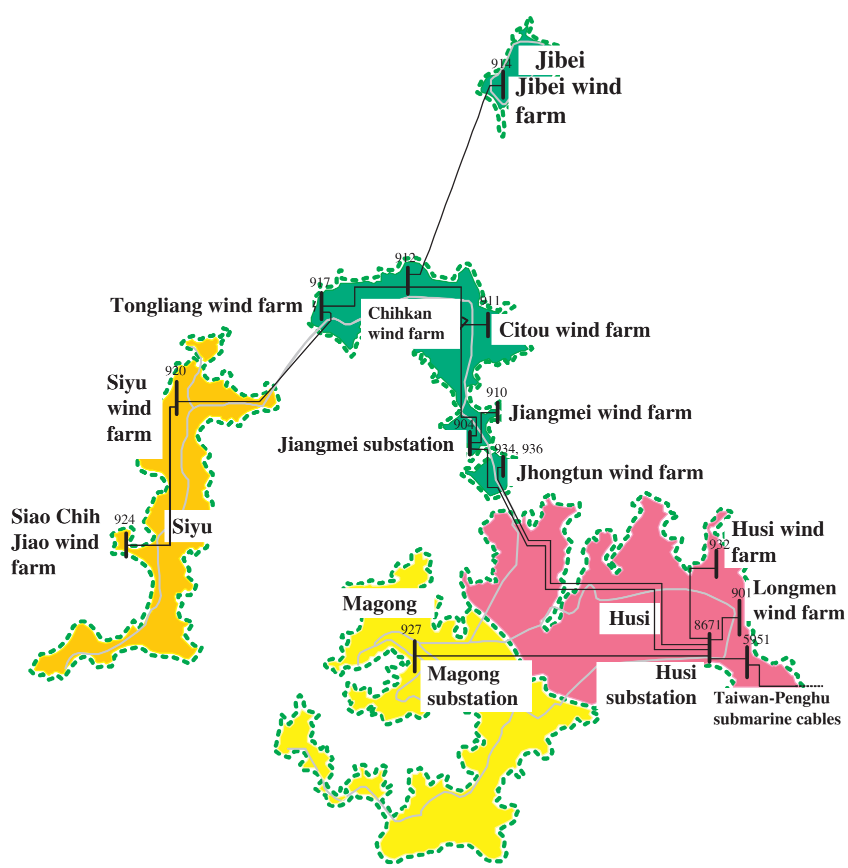

Fig. 2. Single-line schematic diagram of the 143.4 MW Penghu wind power system.

consist of onshore wind farms around the island and include steady-state load flow analysis, fault current analysis, voltage fluctuation analysis, and transient stability analysis. According to load flow analysis results, the load ratio of each line is in the range of 12–71% after wind power is integrated into the system. As fault current is much lower than the rated capacity of system circuit breakers, simulation results show that the increase in fault current before and after grid connection for wind farms is in the range of 1–6 kA. Notably, system voltage fluctuation differs depending on wind turbine control mode. If a wind turbine operates in a control mode with the unity power factor, system voltage may vary significantly due to changes in wind speed. However, if a wind turbine operates in voltage control mode, voltage fluctuation may be low. Moreover, because the dedicated line for connecting wind farms around the island has the capacitor current charging effect, when a wind turbine operates in control mode with the unity power factor, capacitive reactive power in the system will be excessive, leading to voltage increases; therefore, one must install a large number of reactors to absorb excessive reactive power. However, when a wind turbine operates in voltage control mode, the wind turbine can absorb reactive power, voltage can be stabilized to avoid over-voltage, and size of reactors in the system can be reduced significantly to reduce system construction cost. Therefore, wind turbines simulated in this study are operated in voltage control mode. The reactive power of wind turbines in each region is adjusted by setting the voltage at a connection point to 1 pu. For example, when voltage at the connection point is excessively high, a wind turbine will automatically absorb reactive power to maintain stable voltage.

In this study, dynamic simulation and analysis are conducted to determine by simulating whether the system can maintain voltage, frequency, and rotor angle stability [33] when wind speeds fluctuate or major failures occur in the wind power system, and this study further assesses improvement and response measures. Disturbances in a typical power system include changes in transient wind speed, short-circuit ground faults, cable trip-off, wind farm trip-off, and transformer trip-off. This study subjects each possible disturbance to a series of transient stability analyses and compares their impacts on the system under voltage control mode or power factor control mode of wind turbines.

Table 2 shows the representative important cases for simulated items. Instantaneous wind speed change is a frequent system disturbance; thus, it must be considered. The impact of an instantaneous increase or decrease in wind speed on the system must also be assessed. When important power lines or wind farms trip off, the associated impact on the system must be analyzed. The three-phase short-circuit ground fault of buses is also a key factor in transient stability analysis.

Table 2
Transient simulation cases in Penghu System.

Item	Condition	Duration (s)
Variation of wind speed	Wind speed suddenly drops from 14 m/s to 3 m/s	10
	Wind speed suddenly arises from 7 m/s to 14 m/s	10
One of the two-circuit Line trips off	Submarine cable Bus 8671- Bus 927	Continuous
Wind farm trip-off	Siyu wind farm trips off	
Three-phase Short-circuit ground Fault	Bus 928 faults	0.2
	Bus 927 faults	0.2

4.1. Wind speed variation (a sudden rise or drop)

Fig. 3 shows the variation of output from the Jibei Wind Farm when wind speed declines from 14 m/s to 3 m/s within 10 s and the wind turbine is operated in voltage control mode ($V=1$ pu). Active power output dropped from 18 MW to 2.06 MW within 30 s, and absorbed reactive power increased from the initial 1.9 MVAr to 5.89 MVAr to maintain voltage stability. Output voltage at the connection point of the Jibei Wind Farm is very close to the predetermined voltage setting in the range of 1.005–1.0091 pu (Fig. 3). Fig. 4 shows the transient voltage and frequency at the Magong L bus (Bus 927) for the same case. The sudden decline in wind speed has very little effect on system frequency and slightly increases voltage amplitude, which recovers its steady state rapidly, such that the range of voltage fluctuations is small. That is, when the wind farm is operated in constant voltage control mode and wind speed changes, fluctuations to system voltage and frequency remain within an acceptable range. If a wind turbine operated in constant power factor control mode, system voltage is very susceptible to wind speed

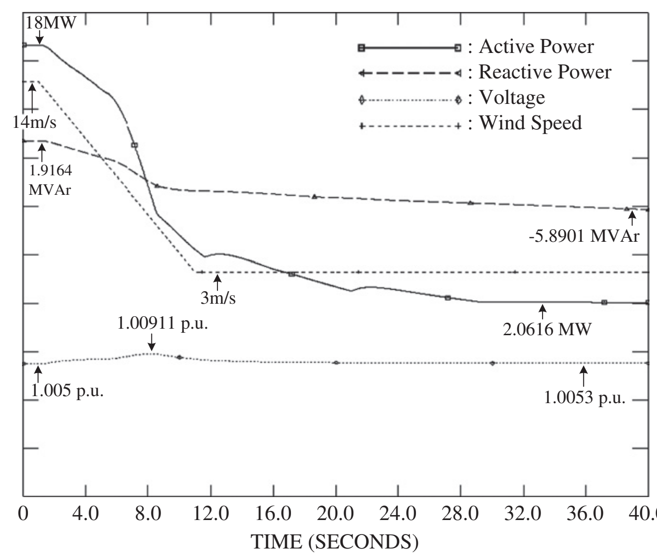

Fig. 3. Output of wind turbines when wind speed suddenly drops (voltage control mode).

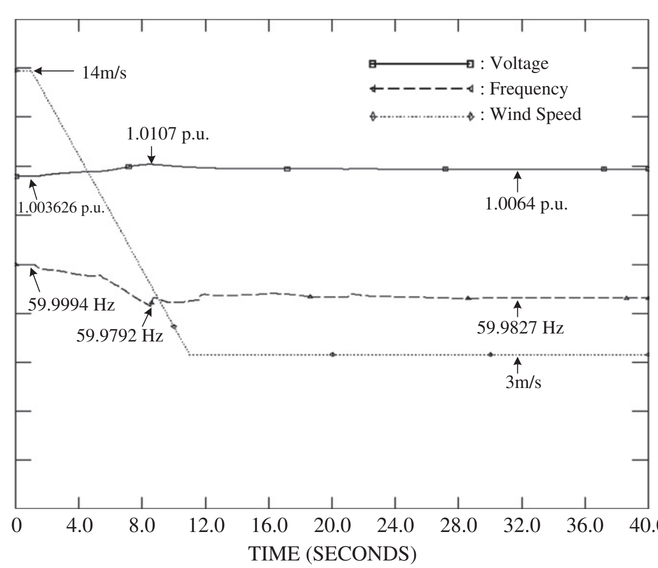

Fig. 4. Voltage and frequency at Magong L bus when wind speed suddenly drops (voltage control mode).

fluctuations, such that reactive power output of the wind turbine will be limited by the constant power factor control mode. Therefore, we suggest that wind turbines in wind farms around Penghu Island should operate in voltage control mode or variable power factor control mode to prevent system voltage from fluctuating significantly due to changes in wind speed.

When wind speed increases rapidly from 7 m/s to 14 m/s within 10 s and wind turbines are operated in voltage control mode in the Jibei Wind Farm (Fig. 5), active power output of the wind farm increases from 4.7 MW to 17.967 MW within 30 s and the absorbed reactive power decreases from the initial 4.4 MVAr to 3.25 MVAr; however, voltage at the connection point of the wind farm is maintained at around 1 pu, and is largely unaffected. However, when the wind turbine is operated in constant power factor control (pf=1) mode, voltage fluctuated markedly at the connection point of the Jibei Wind Farm and additional reactors in the system cannot maintain the system at a constant voltage under different wind speeds; that is, they only increased the difficulty in operating the system.

4.2. N-1 trip-off of important lines

This study simulates an N-1 trip-off of an important line in the Penghu system and its transient effects on system voltage, frequency, and wind farm output. Fig. 6 shows the active and reactive powers of the Jibei Wind Farm when one circuit line in the Penghu submarine cable trips off, and a wind turbine operates in voltage control mode ($V=1$ pu) at full load for power generation. The active power output of the wind farm drops instantly from 18 MW to 16.7 MW when failure occurs but then returns to 18.4 MW immediately, which is only 0.4 MW higher than the original value before failure. However, reactive power output of the wind farm changes from the original absorption of 1.9 MVAr into supply of 2.36 MVAr; this compensates for the charging current effect provided by the original submarine cable. Fig. 7 shows the voltage and frequency waveforms of the Magong L bus for the same case. When one circuit line of the submarine cable trips off, voltage drops to 0.93 pu, but gradually recovers to 0.99 pu within 10 s, which is very close to the original value before the fault. Frequency fluctuation range is 59.99–60.07 Hz. Notably, recovery time of transient voltage drop is as long as 10 s. A further evaluation for the impact of line trip-off on the system

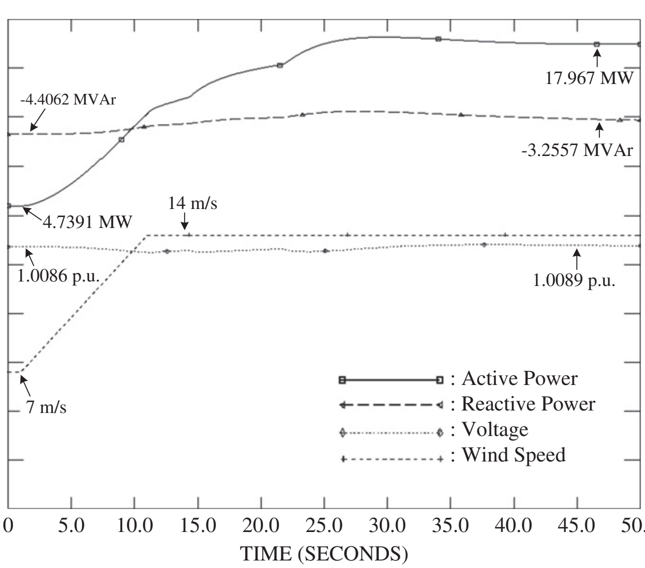

Fig. 5. Output of wind turbines when wind speed suddenly increases (voltage control mode).

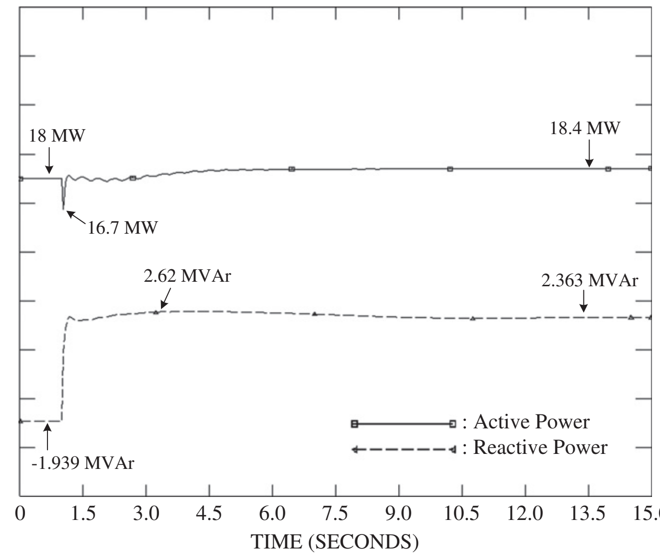

Fig. 6. Output of wind turbines when submarine cable N-1 occurs (voltage control mode).

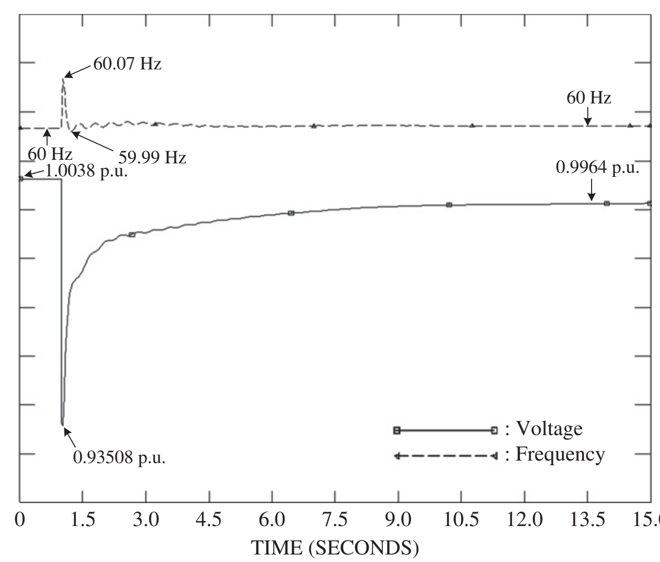

Fig. 7. Voltage and frequency at Magong L bus when submarine cable N-1 occurs (voltage control mode).

and possible improvement strategies is conducted. In this case, when a wind farm is operated in constant power factor control mode, system voltage will not recover to its initial value, but drops by about 0.97 pu. Therefore, some of the inductors in the system must be removed to bring voltage back to 1 pu; however, such an operation may increase system operating complexity.

Another important power transmission line in Penghu system is the 69 kV double-loop dedicated lines that connect the Jianshan Power Plant to the Magong substation. Therefore, Fig. 8 shows the active and reactive power of the Jibei Wind Farm as one circuit line trips off (N-1) when the wind turbine operates in voltage control mode ($V=1$ pu) at full load for power generation. The absorbed reactive power declines from 1.9 MVAr to 1.6 MVAr, which compensates for the charging current effect from the tripped line. Fig. 9 shows voltage and frequency waveforms of the Magong L bus for the same case. The trip off of one dedicated line has a very small impact on system transient voltage and frequency. In this case, even if wind turbine control mode is set to

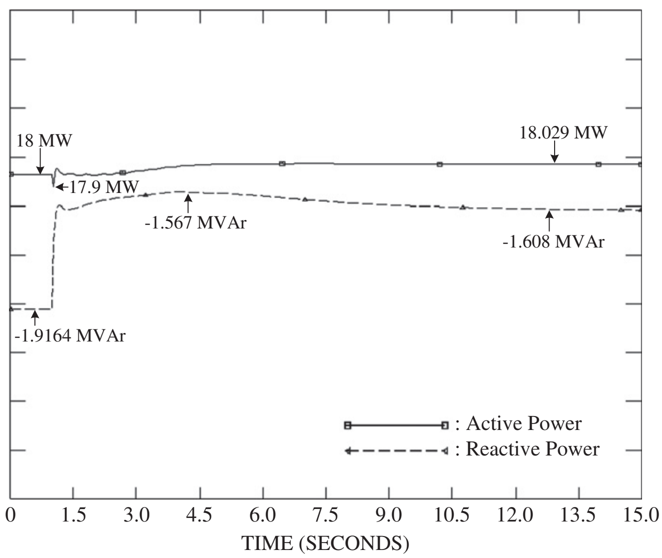

Fig. 8. Output of wind turbines when Magong-Jianshan N-1 trip-off (voltage control mode).

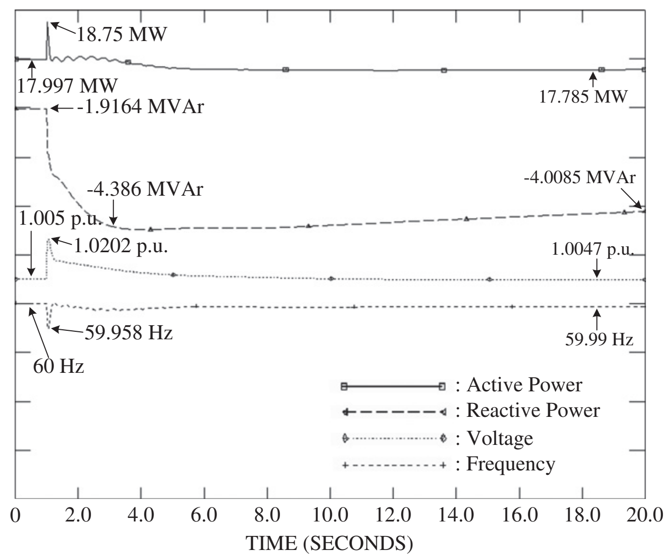

Fig. 10. Output of Jibei wind turbines when Siyu wind farm trips off-line (voltage control mode).

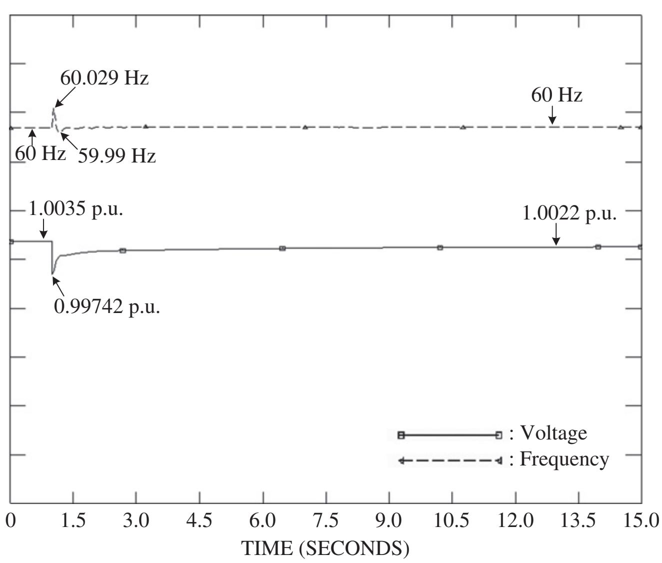

Fig. 9. Voltage and frequency at Magong L bus when Magong-Jianshan N-1 trip-off (voltage control mode).

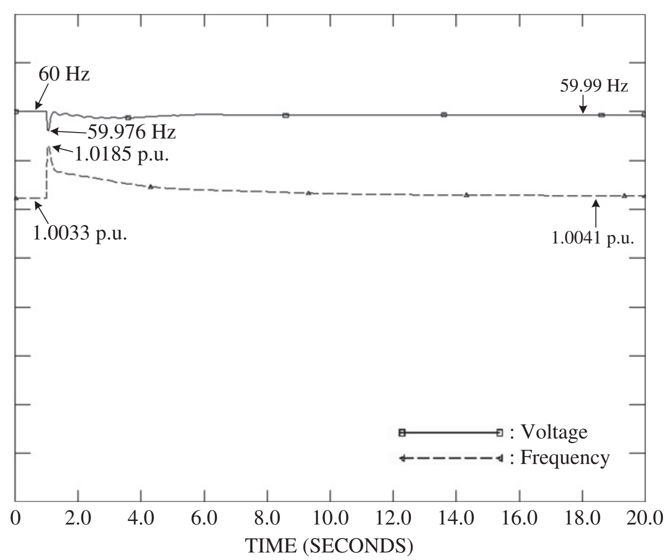

Fig. 11. Voltage and frequency at Magong D1 bus when Siyu wind farm trips off-line (voltage control mode).

power factor control mode, fluctuations in transient voltage and frequency are not significant.

4.3. Single wind farm trip off

This study simulates the impact of a trip off of a wind farm in a single region on system transient stability. We assume that the Siyu Wind Farm trips off and the wind turbine operates in voltage control mode ($V=1$ pu) at full load for power generation. Fig. 10 shows the output response of the Jibei Wind Farm. Active power output of the Jibei Wind Farm recovers to a steady state after a small fluctuation and decreases slightly by 0.2 MW after the trip off. However, reactive power output increases from the original absorption of 1.9 MVAr to 4 MVAr; this increase is due to the distribution of excessive reactive power in the system that is absorbed by other wind farms after the trip off of the Siyu Wind Farm. Fig. 11 shows voltage and frequency waveforms of the Magong D1 Bus for the same case. The trip off of the Siyu Wind Farm has a very limited effect on system transient voltage or frequency.

According to simulation results, the Siyu Wind Farm trip off will not cause a chain reaction of trip offs of other wind farms. Additionally, the trip off of any one wind farms on Penghu Island will not disconnect any other wind farm and system transient voltage can be maintained within specifications.

4.4. Three-phase short-circuit ground fault

Short-circuit ground-fault simulation is a common method of assessing system transient stability. A short-circuit fault may cause an excessively low transient voltage or a large frequency fluctuation and then trigger under-voltage or low-frequency protection relays, causing disconnection of the wind turbine or any system component. Finally, a massive power outage may occur. This study simulates three-phase short-circuit ground faults of the important 69 kV and 11.4 kV buses in the Penghu system to assess their impacts on system stability.

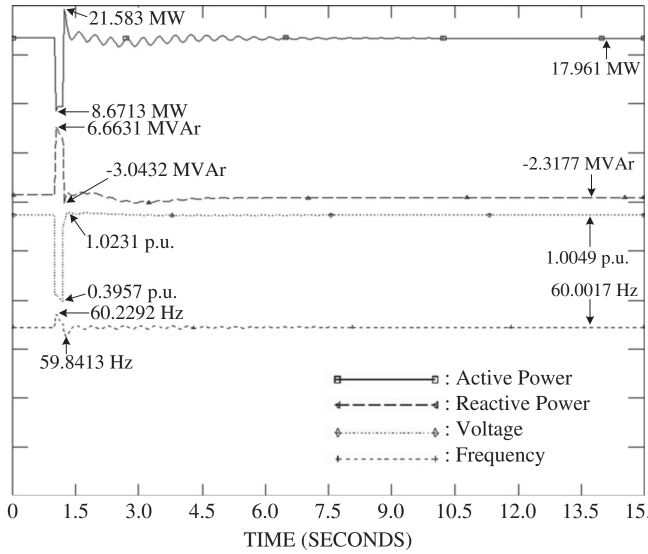

Fig. 12. Output of Jibei wind turbines when Magong D1 bus faults (voltage control mode).

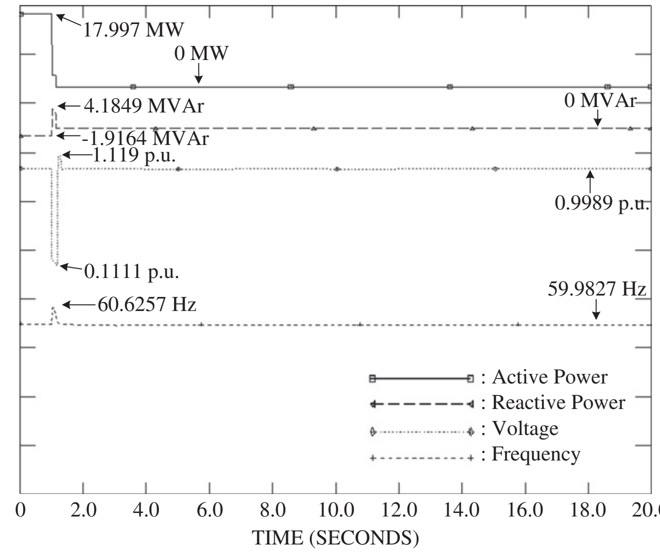

Fig. 14. Output of Jibei wind turbines when Magong L bus faults (voltage control mode).

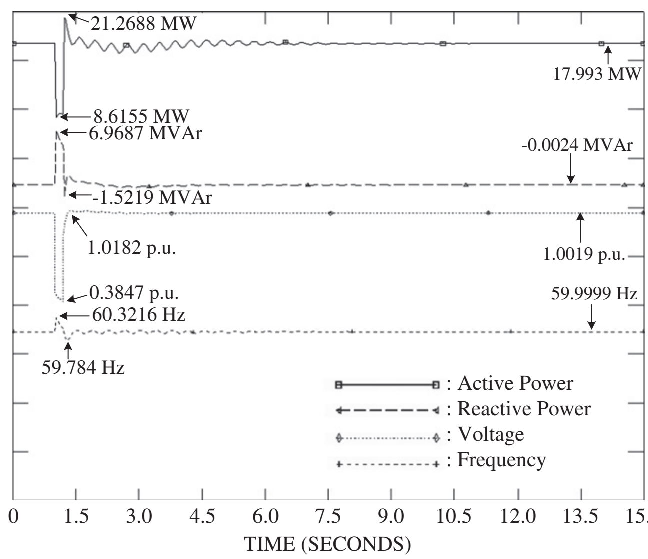

Fig. 13. Output of Jibei wind turbines when Magong D1 bus faults (power factor control mode).

First, the three-phase short-circuit ground fault of the 11.4 kV bus is simulated and analyzed. Fig. 12 shows the transient response of output of the Jibei Wind Farm when the three-phase short-circuit ground fault of the Magong D1 Bus (Bus 928) occurs. During failure, voltage at the connection point declines instantly to 0.39 pu, such that active power may drop dramatically to 8.67 MW. However, reactive power increases instantly to 6.66 MVAr. After the fault is cleared, active power, reactive power, and voltage and frequency at the connection point recover to the steady state values before the fault occurred. This failure does not disconnect any wind farm and has very limited impact on the system's transient stability. This failure case is based on the assumption that a wind turbine operates in constant voltage control mode. Fig. 13 shows transient response of the Jibei Wind Farm when operation mode of the wind turbine is changed to constant power factor control mode. A comparison of simulation results indicates that the choice of operation mode has no effect on system transient response before and after a ground fault occurs.

According to simulation results, when any 11.4 kV bus in the system has a three-phase short-circuit ground fault, no wind farm will be disconnected. However, during the fault, transient under voltage and a slight frequency fluctuation (range 59.8–60.1 Hz) may occur.

In addition to the simulation of 11 kV bus failure, this study also explores the impact of short-circuit failure of the 69 kV bus on the system. Fig. 14 shows the transient response of output by the Jibei Wind Farm when a short-circuit ground fault of the Magong L Bus (Bus 927) occurs. During failure, voltage at the connection point for the wind farm instantly drops to 0.11 pu. Although reactive power output of the wind farm may increase to 4.18 MVAr instantly, excessive under-voltage may still disconnect wind turbines. According to simulation results, as long as the three-phase short-circuit ground fault of any 69 kV bus in the system occurs and if a wind turbine has low-voltage ride-through (LVRT) capability that complies with the technical guidelines for connection of renewable energy power generation systems stipulated by Taipower, then all wind turbines in wind farms on Penghu may disconnect from the system due to under voltage.

Notably, once all wind farms trip off and disconnect from the system, the system will generate an excessively high voltage; this is because wind farms are no longer able to absorb excessive capacitive reactive power in the system. Therefore, the system must rapidly incorporate relevant compensation elements such as inductors or other power system control components. As the simulation result for this case shows (Fig. 14), wind farms are disconnected and system voltage increases instantly to 1.119 pu. However, follow-up connection of inductors within 0.1 s into the system can restore voltage back to a stable value close to 1 pu.

5. Conclusions

The low-carbon island project in Penghu demonstrates Taiwan's capability in developing renewable energy and low-carbon sustainable operations. Project outcomes will affect Taiwan's determination in promoting green energy homes in the future. A high proportion of renewable energy projects in many countries select islands as starting points because the cost of electricity for islands is relatively high and the load is quite small. Thus, outcomes of installing renewable energy equipment can be easily identified.

Penghu has abundant wind resources, and may become a low-carbon island via the development of large onshore and offshore wind farms. The purpose of this study is to plan wind farm sites and power transmission network architecture around Penghu Island and to conduct simulations and analysis of the planned system. According to simulation results, we assert that the operation mode of wind turbines should be constant voltage control mode and a response measure must be provided to prevent system overvoltage when most wind farms disconnect from the system. Simulation results also demonstrate that for an instantaneous change in wind speed, the impacts of N-1 trip off of important lines, trip off of a single wind farm, or three-phase short-circuit ground fault of one 11.4 kV bus on transient stability are within specifications. Therefore, the wind power system on Penghu Island will be of practical value for field applications. Through simulation and analysis of the actual system while considering various possible system fluctuations, this study should contribute to the construction of large wind power facilities, moving Penghu toward low-carbon-island status.

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